

# Spectral Index of the H<sub>2</sub>O-Maser Emitting Planetary Nebula IRAS 17347-3139

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## ABSTRACT

We present radio continuum observations of the planetary nebula (PN) IRAS 17347-3139 (one of the only two known to harbour water maser emission), made to derive its spectral index and the turnover frequency of the emission. The spectrum of the source rises in the whole frequency range sampled, from 2.4 to 24.9 GHz, although the spectral index seems to decrease at the highest frequencies ( $0.79 \pm 0.04$  between 4.3 and 8.9 GHz, and  $0.64 \pm 0.06$  between 16.1 and 24.9 GHz). This suggests a turnover frequency around 20 GHz (which is unusual among PNe, whose radio emission usually becomes optically thin at frequencies  $< 10$  GHz), and a relatively high emission measure ( $1.5 \times 10^9 \text{ cm}^{-6} \text{ pc}$ ). The radio continuum emission has increased by a factor of  $\simeq 1.26$  at 8.4 GHz in 13 years, which can be explained as expansion of the ionized region by a factor of  $\simeq 1.12$  in radius with a dynamical age of  $\simeq 120$  yr and at an expansion velocity of  $\simeq 5 - 40 \text{ km s}^{-1}$ . These radio continuum characteristics, together with the presence of water maser emission and a strong optical extinction suggest that IRAS 17347-3139 is one of the youngest PNe known, with a relatively massive progenitor star.

**Key words:** planetary nebulae: general - planetary nebulae: individual: IRAS 17347-3139 - radio continuum: ISM - stars: AGB and post-AGB

## 1 INTRODUCTION

Maser emission of different molecules (SiO, OH, H<sub>2</sub>O) is observed in evolved stars, from red giants through to planetary nebulae (PNe). This emission seems to be stratified in the envelopes of AGB stars, with SiO masers located close to the stellar surface, water masers at  $\simeq 10 - 100 \text{ AU}$ , and OH masers further away, up to  $\simeq 10^4 \text{ AU}$  (Reid & Moran 1981; Lane et al. 1987). In the evolution of an AGB star to a PN, masers disappear sequentially, starting from the innermost ones (Lewis 1989). Only water and OH masers are generally found in proto-PNe, but as the star enters its PN phase, water molecules are rapidly destroyed by the ionizing radiation (Lewis 1989; Gómez et al. 1990). Therefore water masers are not expected in PNe unless these are extremely young. The first detection of water maser emission in a PN was obtained in K3-35 (Miranda et al. 2001). Maser emission in this source is observed distributed in a disk-like structure around the central star as well as at the tips of a bipolar jet.

Recently de Gregorio-Monsalvo et al. (2004, hereafter

DG04) carried out a survey for water maser emission toward a sample of 26 PNe, to check whether water masers are relatively common toward these kind of objects or if K3-35 is an extraordinary case. As a result of this work they detected a new cluster of water masers toward the southern source IRAS 17347-3139, which constitutes the second bona-fide PN known to show water maser emission. The low rate of detection (1 out of 26) is statistically compatible with the short ( $\simeq 100 \text{ yr}$ ) lifetime of water molecules in the envelopes of PNe.

Very Large Array (VLA) maps of IRAS 17347-3139 (DG04) show 13 maser components, distributed in an ellipse with axes  $\simeq 0''.25 \times 0''.12$  ( $\simeq 200 \times 100 \text{ AU}$  at 0.8 kpc), with the 22 GHz radio continuum emission located at one of the tips of its major axis (DG04). This suggests a possible binary nature for this source, with the radio continuum emission related to the central star, and the water maser ellipse associated to a companion.

The radio continuum emission of IRAS 17347-3139 shows a spectral index  $\alpha = 0.76 \pm 0.03$  ( $S_\nu \propto \nu^\alpha$ ) between

4.9 and 14.9 GHz (DG04), consistent with a partially optically thick ionized region. However, the flux density at 22 GHz was significantly lower than the value expected from the spectral index of 0.76 found at lower frequencies. This discrepancy could be explained as a combination of source variability (the 22 GHz data were taken 11 years later than those at lower frequencies), calibration errors (given the low elevation of this southern source from the VLA), extended emission ( $\gtrsim 5''$ ) not sampled by the VLA, or a change in the opacity regime.

The last possibility is especially compelling. If the ionized region becomes optically thin between 14.9 and 22 GHz, one would expect a flat spectral index at frequencies higher than the turnover frequency. Knowing the turnover frequency of the ionized region would allow us to measure some of its physical parameters. Obviously quasi-simultaneous radio continuum observations from a southern telescope were necessary to rule out variability and calibration effects, and to determine whether the turnover frequency of the emission is indeed around 20 GHz. The flux density and spectral index of radio-continuum emission can provide interesting information about the ionized region and, by inference, also about the physical characteristics of the central star. Given that water maser emission is a rare phenomenon in PN and that it is thought to be present only among the youngest ones it is important to study in detail IRAS 17347-3139 to see whether we can find some special characteristics that may be related to its ability to pump water masers.

In this paper we present a new, detailed study of the spectral index of IRAS 17347-3139 between 2.4 and 24.9 GHz. In Sec. 2 we describe our observations and we discuss our results in Sec. 3.

## 2 OBSERVATIONS AND RESULTS

Radio continuum observations of IRAS 17347-3139 were carried out with the Australia Telescope Compact Array (ATCA)<sup>1</sup> of the Australia Telescope National Facility, on 2004 March 4 and 10. We observed at 11 different frequencies between 1.4 and 25 GHz on both days. However, the data at 1.4 GHz were not useful due to interference. The total bandwidth in all cases was 128 MHz, sampled over 14 channels. The source PKS 1934-638 was used as the primary flux calibrator, while IVS B1759-396 was the phase calibrator. Flux densities for those calibrators are shown in Table 1. The phase center of our observations was located at  $\alpha(\text{J2000}) = 17^{\text{h}}38^{\text{m}}00^{\text{s}}.586$ ,  $\delta(\text{J2000}) = -31^{\circ}40'55''.67$ , the position of the radio continuum emission from IRAS 17347-3139 (DG04).

Initial calibration of the data was made using the MIRIAD package, while self-calibration (in both phase and amplitude) and deconvolution was performed with Difmap and AIPS. After checking that the resulting flux densities of IRAS 17347-3139 at each frequency were compatible, within the errors, for data taken on March 4 and 10 (thus ruling out source variability at timescales of days and significant calibration errors), we combined the data of both periods to

**Table 1.** Flux densities of calibrators

Frequency (GHz)	$S_f^a$ (Jy)	$S_{p1}^b$ (Jy)	$S_{p2}^c$ (Jy)
2.368	11.59	1.51	1.51
4.288	6.62	1.49	1.40
6.080	4.40	1.56	1.44
8.128	3.07	1.62	1.55
8.896	2.74	1.63	1.57
16.064	1.24	1.57	1.55
18.496	1.02	1.56	1.53
21.056	0.88	1.56	1.60
22.976	0.80	1.57	1.63
24.896	0.74	1.56	1.64

<sup>a</sup> Assumed flux density of PKS 1934-638

<sup>b</sup> Bootstrapped flux density of IVS B1759-396 on 2004 March 4. Uncertainties are  $\simeq 0.03$  Jy

<sup>c</sup> Bootstrapped flux density of IVS B1759-396 on 2004 March 10. Uncertainties are  $\simeq 0.03$  Jy

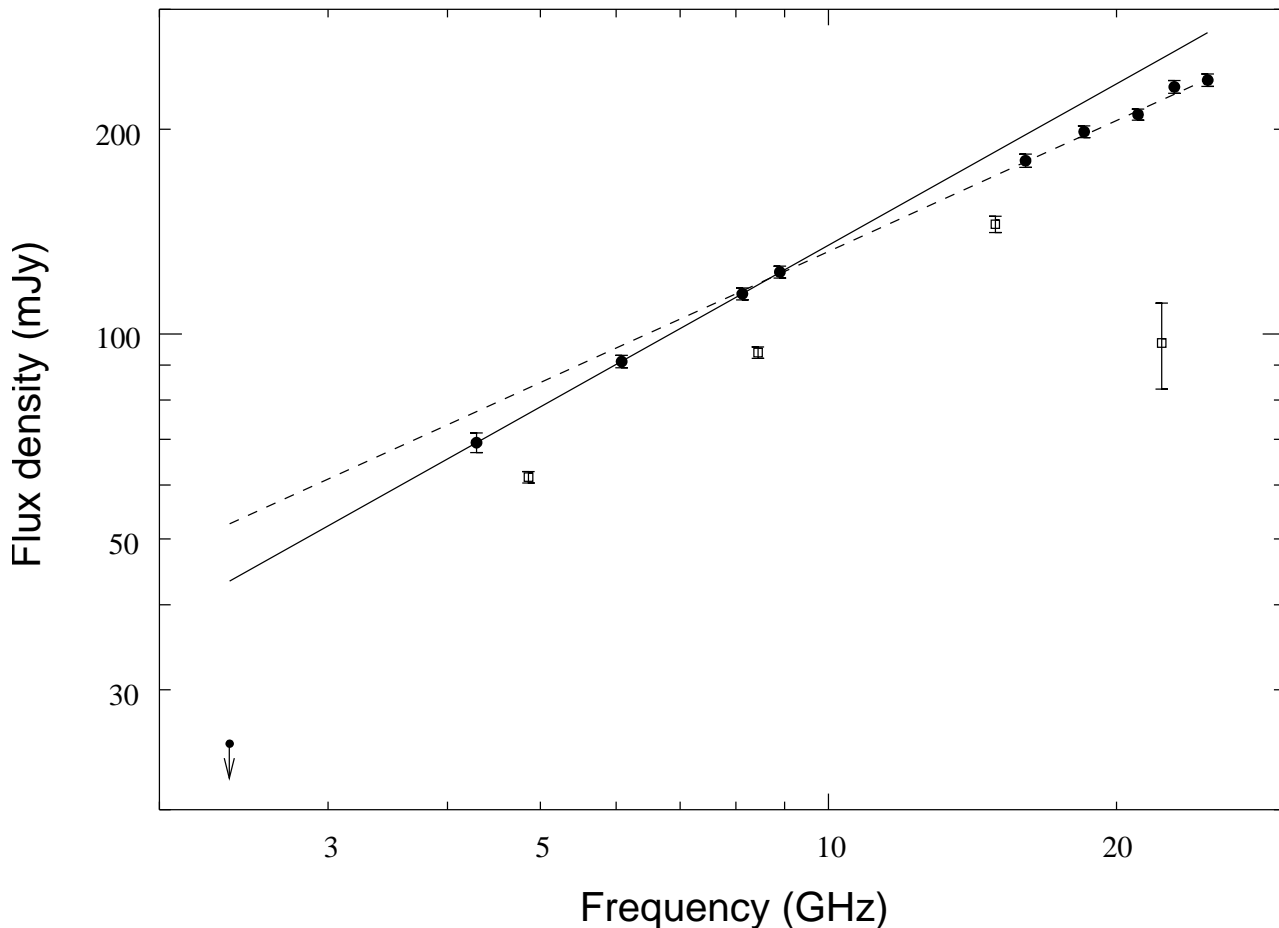
**Table 2.** Continuum emission of IRAS 17347-3139

Frequency (GHz)	Flux Density (mJy)	Beam size (arcsec)	Beam P.A. (deg)
2.368	< 25	$16.6 \times 4.8$	-33.1
4.288	$69.2 \pm 2.3$	$10.0 \times 2.7$	-29.0
6.080	$91.1 \pm 1.9$	$7.1 \times 2.0$	-29.4
8.128	$114.6 \pm 2.3$	$5.7 \times 1.3$	-25.7
8.896	$123.3 \pm 2.5$	$5.3 \times 1.2$	-25.7
16.064	$180 \pm 4$	$2.2 \times 0.6$	-15.3
18.496	$198 \pm 4$	$2.0 \times 0.5$	-16.2
21.056	$210 \pm 4$	$1.7 \times 0.4$	-21.0
22.976	$231 \pm 5$	$1.5 \times 0.4$	-25.6
24.896	$236 \pm 5$	$1.3 \times 0.5$	-29.7

improve the uv coverage. Table 2 and Fig. 1 summarize the final results of our measurements of flux density in IRAS 17347-3139.

The point at 2.4 GHz is given as an upper limit although the map shows emission of  $\simeq 10$  mJy near the position of the radio continuum emission of IRAS 17347-3139 at other frequencies. However there is a relatively strong extragalactic source, TXS 1734-314, within the primary beam with a flux density of  $\simeq 995 \pm 20$  mJy at 2.4 GHz and peak intensity located at  $\alpha(2000) = 17^{\text{h}}37^{\text{m}}43^{\text{s}}.4$ ,  $\delta(2000) = -31^{\circ}31'10''$  (but undetected at the other frequencies). TXS 1734-214 produces sidelobes stronger than 10 mJy, and therefore, we cannot be certain that the emission apparently associated to IRAS 17347-3139 at 2.4 GHz is real, and even if it is, we cannot determine its flux density properly. Source confusion makes snapshot data from a linear array like ATCA difficult to calibrate and process (Burgess & Hunstead 1995), especially at the deconvolution stage. The upper limit we give in Table 2 is the flux density of the strongest sidelobe in the map. A more accurate determination or upper limit on the 2.4 GHz flux density of IRAS 17347-3139 would require imaging the field of view with better uv coverage. With this upper limit we estimate a spectral index  $\alpha \geq 1.7$  between 2.4 and 4.3 GHz which is consistent with the ionized region being in the optically thick regime at 2.4 GHz, since we expect a spectral index  $\alpha \simeq 2$  in that case.

<sup>1</sup> The Australia Telescope Compact Array is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO



**Figure 1.** Flux density of IRAS 17347-3139 as a function of frequency. Filled circles represent ATCA data (2004 March). Open squares represent VLA data (1991 February, except the point at 22 GHz, taken on 2002 July). The solid line is the best fit for ATCA data at  $\nu < 9$  GHz (spectral index = 0.79). The dashed line is the fit for  $\nu > 16$  GHz (spectral index = 0.64)

For the detected emission, from 4.3 to 24.9 GHz, the spectrum of IRAS 17347-3139 rises with increasing frequency. This is not consistent with our result in DG04 using the VLA in which the flux density seemed to drop at 22 GHz. We think this discrepancy is most likely due to calibration errors in the VLA data at these high frequencies and at low elevation, or to extended emission ( $\gtrsim 5''$ ) being resolved out by the VLA.

A careful analysis of the spectral index (Fig. 1) shows that it is decreasing at the highest frequencies. We estimate an index of  $0.79 \pm 0.04$  between 4.3 and 8.9 GHz (consistent with our VLA estimate of  $0.76 \pm 0.03$ , DG04) whereas the values of flux densities at  $\nu > 16$  GHz are slightly but significantly lower than those expected from the extrapolation of the lower frequency fluxes. We derive a spectral index of  $0.64 \pm 0.06$  between 16.1 and 24.9 GHz.

Therefore it seems that the radio continuum emission is becoming optically thin around the highest frequencies we sampled, as suggested in DG04. Of course an accurate determination of the turnover frequency would require observations at frequencies even higher than 24 GHz to reach the region of the spectrum where the spectral index would be  $\simeq 0$ .

It is noticeable that the spectral index does not change much over a wide range of frequencies (from 4.3 to 24.9

GHz), rather than showing a rapid transition between the optically thick and thin regimes, which would occur in the case of an homogeneous HII region. Such relatively constant spectral indices are expected in ionized regions with a power-law decrease of electron density with distance from the central star (Olson 1975; Panagia & Felli 1975; Wright & Barlow 1975). In our case an average spectral index of  $\alpha \simeq 0.7$  would require the electron density to vary as  $n_e \propto r^{-2.1}$ , where  $r$  is the distance to the central star. Similar spectral indices are also expected if the radiocontinuum emission arises from a collimated wind, as suggested for the radio core of M2-9 (Kwok et al. 1985; Lim & Kwok 2003). However, as discussed in DG04, in the case of IRAS 17347-3139 the derived mass loss-rate under the assumption of a wind is  $\dot{M} \simeq 1 \times 10^{-4} (D/\text{kpc})^{3/2} M_{\odot} \text{ yr}^{-1}$ , much higher than expected in central stars of PNe and proto-PNe ( $\dot{M} \lesssim 10^{-7} M_{\odot}$ ; Patriarchi & Perinotto 1991; Vassiliadis & Wood 1994), and  $\gtrsim 2$  orders of magnitude larger than the value derived for the core of M2-9 by Lim & Kwok (2003), which was already difficult to explain even if the main source of mass-loss were an AGB star in a symbiotic system. Therefore, in principle we favor that the radio continuum emission arises from an ionized nebula, although higher-resolution observations would be useful to

determine whether there is a collimated radio outflow in IRAS 17347-3139.

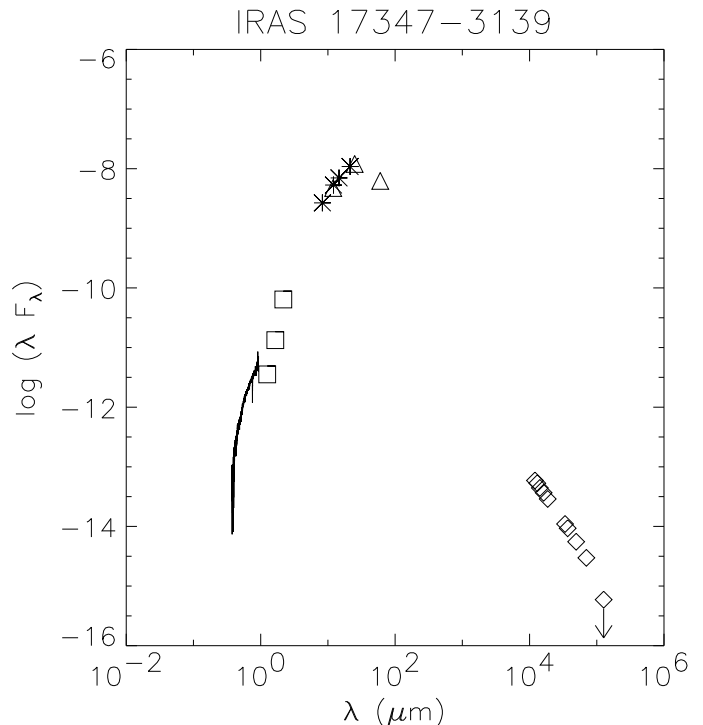
From the decrease in the spectral index at  $\simeq 20$  GHz we can estimate the turnover to be around this frequency. As mentioned in DG04, assuming a turnover frequency of  $\simeq 20$  GHz we derive an emission measure  $EM = 1.5 \times 10^9 \text{ cm}^{-6} \text{ pc}$ . In that paper we estimated a distance of 0.8 kpc based on two methods (evolutionary arguments, and statistical distance). Unfortunately, the statistical distance was incorrect, and it should be  $\simeq 6$  kpc instead of 0.8 kpc (using the scale of Zhang 1995, based on the mass-radius relationship). Therefore we have to consider a distance range of 0.8-6 kpc in the determination of other parameters. We also note that statistical distances for PNe are very uncertain and they can vary up to more than a factor of  $\simeq 3$  depending on the particular scale used (cf. Bensby & Lundström 2001; Phillips 2002, and references therein). With a distance range of 0.8-6 kpc we derive an average electron density  $n_e = 4.1 \times 10^5 - 1.1 \times 10^6 \text{ cm}^{-3}$  for a size of  $0''.3$ .

### 3 DISCUSSION

IRAS 17347-3139 is an unusual PN, since it is one of the only two known to harbour water maser emission. Therefore it is important to look for any other observational characteristics that may be related to the presence of water maser emission.

Several observational signatures, that we will discuss here, strongly suggest that IRAS 17347-3139 is one of the youngest PNe known. First, the turnover frequency of the radio continuum emission in IRAS 17347-3139,  $\simeq 20$  GHz, is abnormally high as compared with other PNe, in which the radio emission is optically thin for frequencies  $> 10$  GHz (e.g., Hughes 1967; Taylor, Pottasch, & Zhang 1987; Zijlstra, Pottasch, & Bignell 1989; Aaquist & Kwok 1991). Noticeable exceptions are AFGL 618 and Hb 12, which have turnover frequencies  $\geq 22$  GHz (Kwok & Bignell 1984) and  $\simeq 30$  GHz (Aaquist & Kwok 1991), respectively. These objects have been proposed to be very young PN ( $\simeq 100$  yr in the case of AFGL 618; Kwok & Bignell 1984). For IRAS 17347-3139, the high turnover frequency is also consistent with this source being a very young PN, since the high emission measure that it implies is a signature of youth (Kwok, Purton, & Keenan 1981).

The optical spectrum of IRAS 17347-3139 shows very few lines. Of particular interest is the absence of  $H\alpha$  emission in the spectrum shown in the atlas of Suárez et al. (2005), while all other objects classified as PN and “transition objects” in this atlas show this line. Only  $[S \text{ III}]$  at  $\lambda 9069 \text{ \AA}$  is clearly detected by Suárez et al. (2005). The absence of optical features in IRAS 17347-3139 can be attributed to an extremely high extinction, which is also evident in its spectral energy distribution (SED; Fig. 2). The SED of IRAS 17347-3139 shows only a peak, at  $\simeq 25 \mu\text{m}$ , with a sharp decrease toward optical wavelengths. The fact that this object shows ionization while still keeping a very thick envelope to produce such a strong extinction suggests a very rapid evolution and therefore implies that the progenitor star was relatively massive (Blöcker 1995). This is also supported by the bipolar morphology of the nebula (DG04), since bipolar PNe seem to be associated with the evolution of more mas-



**Figure 2.** Spectral energy distribution of IRAS 17347-3139, adapted from Suárez et al. (2005). The solid line is the optical spectrum. The squares, asterisks and triangles represent the 2MASS, MSX, and IRAS data, respectively. The diamonds are the ATCA radio continuum measurements (this paper).

sive stars than those producing elliptical or spherical PNe (Corradi & Schwarz 1995).

It is also interesting that the radio flux density of IRAS 17347-3139 seems to have risen in the 13 years between the VLA and ATCA observations (Fig. 1). Assuming that the opacity of the ionized region has not varied significantly (the spectral index is similar in both epochs), a possible explanation of this increase in flux density could be the expansion of the ionized region. At a frequency of  $\simeq 8.4$  GHz, the increase is of a factor of  $\simeq 1.26$ , which would correspond to expansion by a factor of 1.12 in radius in 13 years. At this rate, and assuming a constant expansion velocity, the kinematical age of the ionized region is only  $\simeq 120$  yr. The corresponding linear expansion velocity, assuming a radius of  $\simeq 0''.15$ , at a distance of  $\simeq 0.8 - 6$  kpc would be  $\simeq 5 - 40 \text{ km s}^{-1}$  ( $\simeq 1 - 8 \text{ AU yr}^{-1}$ ). This estimate is consistent with the expansion velocities found in PNe (typically  $\simeq 10 - 35 \text{ km s}^{-1}$ ; Sabadhin 1984; Weinberger 1989). We also note that radio brightening has been reported in AFGL 618 (Kwok & Feldman 1981), also interpreted as expansion of its associated ionized region. An increase of the flux density at radio wavelengths is expected in some models of PN evolution (Volk & Kwok 1985) during the first few hundred years, especially for the most massive cases (see Fig. 14 in Volk & Kwok 1985) while the ionized nebula expands but the optical depth is still high.

The evidence we have presented above, indicating that IRAS 17347-3139 is an extremely young PN, is consistent with the presence of water maser emission since water molecules are thought to be destroyed in  $\simeq 100$  yr

(Gómez et al. 1990). Given the characteristics found in IRAS 17347-3139, we have checked for the possible presence of water masers in AFGL 618 and Hb 12, to see if a rising radio spectrum at  $\simeq 20$  GHz could be an indication of a higher probability of maser emission. Since we did not find in the literature any report of water maser observations toward Hb 12, and given that the  $3\sigma$  upper limit of  $\geq 2.1$  Jy obtained by Wouterloot, Brand, & Fiegle (1993) towards AFGL 618 (IRAS 04395+3601) is relatively high, we took spectra of the  $6_{16} \rightarrow 5_{23}$  transition of the water molecule (rest frequency 22235.080 MHz), with NASA's 70m DSN antenna in Robledo de Chavela (Spain), on 2005 May 20, toward these two PNe. These spectra show no emission, with  $3\sigma$  upper limits of 160 mJy between  $V_{\text{LSR}} = -128.9$  and  $+86.9$  km s $^{-1}$  for AFGL 618, and 130 mJy between  $V_{\text{LSR}} = -112.7$  and  $+103.0$  km s $^{-1}$  for Hb 12 (with a velocity resolution of 0.56 km s $^{-1}$  in both cases).

We note that K3-35, the other PN known to show water maser emission (Miranda et al. 2001), does not have a rising spectrum at this frequency (its turnover frequency is  $\simeq 10$  GHz; Aaquist & Kwok 1991) nor a strongly obscured optical spectrum (it shows emission of H $\alpha$  and other prominent optical lines; Miranda et al. 2000), which could indicate that this source may be in a later evolutionary stage than IRAS 17347-3139.

All the unusual characteristics of IRAS 17347-3139 suggest that this could be one of the youngest ( $< 100$  year) PNe known, and therefore, it is one of the most appropriate objects to further study the early stages of this phase of stellar evolution, together with other PNe with rising spectra at high radio frequencies.

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